

**WHAT IS CLAIMED IS:**

1           1.     A method of etching openings in a dielectric layer with profile  
2     control, comprising:  
3           supporting a semiconductor substrate in a plasma etch reactor, the substrate  
4     including a dielectric layer;  
5           supplying an etchant gas to the plasma etch reactor; and  
6           etching openings in the dielectric layer by energizing the etchant gas into a  
7     plasma state, the etchant gas comprising  $C_xF_yH_z$  wherein  $x \geq 1$ ,  $y \geq 1$  and  $z \geq 0$ , a  
8     sulfur-containing gas and an oxygen-containing gas, the sulfur-containing gas and  
9     the oxygen-containing gas being added in amounts effective for profile control of  
10    the etched openings.

1           2.     The method of Claim 1, wherein the openings comprise vias,  
2     contacts, and/or trenches of a dual damascene, self-aligned contact or self-aligned  
3     trench structure.

1           3.     The method of Claim 1, wherein the  $C_xF_yH_z$  forms a protective  
2     sidewall polymer on sidewalls of the etched openings, the sulfur-containing gas  
3     protects the sidewall polymer from excessive attack by the oxygen-containing gas  
4     and the oxygen-containing gas maintains a desired thickness of the sidewall  
5     polymer.

1           4.     The method of Claim 1, wherein the plasma etch reactor comprises  
2     an ECR plasma reactor, an inductively coupled plasma reactor, a capacitively  
3     coupled plasma reactor, a helicon plasma reactor or a magnetron plasma reactor.

1           5.     The method of Claim 1, wherein the plasma etch reactor comprises  
2     a dual frequency capacitively coupled plasma reactor including an upper  
3     showerhead electrode and a bottom electrode, RF energy being supplied at two  
4     different frequencies to either the bottom electrode or at different first and second  
5     frequencies to the showerhead electrode and bottom electrode.

1           6.     The method of Claim 1, wherein the sulfur-containing gas is SO<sub>2</sub>  
2     and the oxygen-containing gas is O<sub>2</sub>, the SO<sub>2</sub> and O<sub>2</sub> being added in amounts  
3     effective to provide undissociated SO<sub>2</sub> molecules which react with polymer at  
4     bottoms of the etched openings to prevent etch stop under bombardment of  
5     directional ions.

1           7.     The method of Claim 1, wherein the ratio of flow rates of the  
2     sulfur-containing gas to the oxygen-containing gas is 0.5:1 to 1.5:1.

1           8.     The method of Claim 1, wherein pressure in the plasma etch reactor  
2     is 5 to 200 mTorr and/or temperature of the substrate support is -20°C to +80°C.

1           9.     The method of Claim 1, wherein the plasma etch reactor is a  
2           capacitively coupled plasma reactor having a powered showerhead electrode and a  
3           powered bottom electrode, the showerhead electrode being supplied 500 to 3000  
4           watts of RF energy and the bottom electrode being supplied 500 to 3000 watts of  
5           RF energy.

1           10.    The method of Claim 1, wherein the etchant gas includes a carrier  
2           gas selected from the group consisting of He, Ne, Kr, Xe and Ar, the carrier gas  
3           being supplied to the plasma etch reactor at a flow rate of 5 to 1000 sccm.

1           11.    The method of Claim 1, wherein the dielectric layer comprises a  
2           doped or undoped silicon dioxide, BPSG, BSG, FSG, PSG, TEOS, thermal silicon  
3           oxide or inorganic low-k material or organic low-k material, the dielectric layer  
4           overlying a conductive layer selected from the group consisting of Al, Al alloys,  
5           Cu, Cu alloys, Ti, Ti alloys, doped or undoped polycrystalline or single crystal  
6           silicon, TiN, TiW, Mo, silicides of Ti, W, Co and/or Mo or alloys thereof, the  
7           semiconductor substrate including an optional stop layer and/or mask layer  
8           selected from silicon nitride, silicon carbide or silicon oxynitride over the  
9           dielectric layer and/or between the dielectric and conductive layer.

1           12.    The method of Claim 1, wherein the sulfur-containing gas is SO<sub>2</sub>  
2           and the oxygen-containing gas is O<sub>2</sub>, each of the SO<sub>2</sub> and O<sub>2</sub> gases being supplied  
3           to the plasma etch reactor at a flow rate of 1 to 30 sccm.

1           13.    The method of Claim 1, wherein the dielectric layer is BPSG and  
2           the etchant gas includes SO<sub>2</sub> and O<sub>2</sub> supplied to the plasma etch reactor with flow  
3           rates providing a SO<sub>2</sub>:O<sub>2</sub> flow rate ratio of 1:2 to 2:1.

1           14.    The method of Claim 1, wherein the etched openings are 0.30 μm  
2           or smaller sized openings having substantially straight profiles wherein top, middle  
3           and bottom critical dimensions of the openings are substantially the same, and the  
4           openings have an aspect ratio of at least 5:1.

1           15.    The method of Claim 1, wherein the dielectric layer includes a stack  
2           of layers of low-k materials with or without etch stop layers therebetween, the  
3           openings being etched to depths of at least 2 μm.

1           16.    The method of Claim 1, wherein an RF bias is applied to the  
2           semiconductor substrate during the etching step.

1           17.     The method of Claim 1, wherein the etched openings are 0.25  $\mu\text{m}$   
2           or smaller sized openings having substantially straight profiles wherein top, middle  
3           and bottom critical dimensions of the openings are substantially the same, and the  
4           openings have an aspect ratio of at least 10:1.

1           18.     The method of Claim 1, wherein the etchant gas includes  $\text{C}_4\text{F}_8$ ,  $\text{SO}_2$ ,  
2            $\text{O}_2$  and Ar supplied to the plasma etch reactor at flow rates of 5 to 30 sccm  $\text{C}_4\text{F}_8$ , 2  
3           to 15 sccm  $\text{SO}_2$ , 2 to 15 sccm  $\text{O}_2$ , and 300 to 600 sccm Ar.

1           19.     The method of Claim 1, wherein the etchant gas includes  $\text{C}_4\text{F}_8$ ,  $\text{SO}_2$ ,  
2            $\text{O}_2$  and Ar supplied to the plasma etch reactor at flow rates of 10 to 20 sccm  $\text{C}_4\text{F}_8$ ,  
3           4 to 10 sccm  $\text{SO}_2$ , 4 to 10 sccm  $\text{O}_2$ , and 450 to 550 sccm Ar.

1           20.     The method of Claim 1, wherein  $\text{C}_x\text{F}_y\text{H}_z$  comprises at least one  
2           hydrogen-free fluorocarbon selected from  $\text{CF}_4$ ,  $\text{C}_2\text{F}_2$ ,  $\text{C}_2\text{F}_4$ ,  $\text{C}_3\text{F}_6$ ,  $\text{C}_4\text{F}_6$ ,  $\text{C}_4\text{F}_8$  and  
3            $\text{C}_6\text{F}_6$  and/or at least one hydrogen-containing fluorocarbon selected from  $\text{C}_2\text{HF}_3$ ,  
4            $\text{CHF}_3$ ,  $\text{CH}_3\text{F}$ ,  $\text{C}_3\text{H}_2\text{F}_6$ ,  $\text{C}_3\text{H}_2\text{F}_4$ ,  $\text{C}_3\text{HF}_5$ ,  $\text{C}_3\text{HF}_7$ .